The Autonomous Ground Vehicle RASCAL: Team SciAutonics/Auburn Engineering in the DARPA Grand Challenge 2005*

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Abstract

RASCAL is the autonomous ground vehicle of the team SciAutonics/Auburn-Engineering. In the 2004 DARPA Grand Challenge, it went 0.75 miles. For 2005, the team has improved the architecture and the software to allow faster operation, and better deal with obstacle detection. The vehicle uses closed-loop control using differential GPS and an inertial navigation system (INS) for navigation. Two Linux-based computers process sensing input from the GPS, INS, and other vehicle state sensors, along with LIDAR, ultrasound, and stereo vision sensors for real time obstacle avoidance. RASCAL can track waypoints at 25 mph and avoid collisions while driving at 16 mph.

Introduction

Our team was formed in March 2003, in response to the announcement of the DARPA Grand Challenge 2004. Initially it comprised a team of scientists and engineers from **Rockwell Scientific (RSC)** of Thousand Oaks, CA, although many volunteers from other companies have joined the team.[1] A limited liability company, **SciAutonics, LLC**, was created as the legal entity for ownership of the vehicle and accessories and for participation in the event. SciAutonics LLC currently has no paid employees but the company will own the team intellectual property and is positioned to transition into a company that will exploit its autonomous vehicle technology after the Grand Challenge series is complete. Our fundraising approach is to invite companies and individuals, including many of our volunteers, to invest in SciAutonics LLC. Key investors are Rockwell Scientific and **ATV Corporation**, ATV Corporation having provided our two ATV Prowler vehicles, RASCAL-1 (our Challenge vehicle) and RASCAL-2. **Amgen**, a Thousand Oaks based biotechnology company, has provided computing hardware for RASCAL and several Amgen employees are team members. Another key partner is the **Engineering School of Auburn University** who has developed the vehicle closed loop control system. For the Grand Challenge 2005, we reflect this close collaboration in our team name '**SciAutonics/Auburn-**

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[1] Our volunteers are employed at numerous companies including Amgen and Teradyne in the Thousand Oaks area and a number of our volunteers are Rockwell Scientific retirees.

Engineering”. Finally, we have also teamed with **ARC Seibersdorf** who has provided their stereovision system for feature detection.

Support for our mapping task and waypoint file creation comes from volunteers employed by **Vestra**, Inc, **ESRI** and the **City of Thousand Oaks**.

RASCAL is designed to follow GPS waypoints while continuously sensing the terrain ahead and making real time corrections to the course in order to avoid driving off the road or colliding with obstacles. The vehicle control system (the control module) directs the vehicle by comparing the actual position (sensed by GPS or the IMU during GPS outages) to the desired position and minimizing the error by correcting the steer angle using a closed loop feedback control approach. In real time, while the vehicle is driving autonomously, a suite of sensors (LIDAR, stereovision, and ultrasound) is continuously sensing the terrain ahead of the vehicle. As objects are sensed (including road edges where possible, as well as static objects), the locations of undrivable areas are placed in a virtual map (that has real world coordinates) within the feature manager module. Data from this map are passed to the path planner module. The path planner then overlays the a priori route (based on the RDDF file) onto the object field map and recomputes a new pathway to avoid obstacles while staying within the allowed lateral offsets. Once an obstacle is avoided, the recomputed route reconverges with the a priori route. This recomputed path is then fed to the vehicle controller and the vehicle control system has RASCAL follow the recomputed path. The path planner will also limit speed predicated on the radii of curvature defined by the recomputed route.

Figure 1. Team SciAutonics/Auburn-Engineering (although a number of members could not be present.).

Vehicle

The vehicle is based on a 2003 ATV Prowler, made by ATV Corporation (Orange, CA). It has a low center of gravity, it is rugged for off-road driving, it has four-wheel drive with an automatic continuously variable transmission (CVT), and a high-speed capability (55 mph driven by human driver on or off-road).

Modifications have been made to the suspension system to accommodate the increased weight of computers and sensors. All vehicle changes made for autonomous operation have been made such that human driver operation is not precluded – the human-operation pedals (brake, throttle) are in place, and the driver can (with large force) override the steering servo.

Figure 2. RASCAL vehicle before customization and hardware installations (November 2003).

Autonomous Operation

The emphasis in designing our system architecture was on simplicity and modularity: failure of one component was not to affect the functionality of the main components. Therefore, our concept consists of independent modules that provide auxiliary information to the main driving module. At the core is the vehicle control actuation system, which controls steering, brake, throttle, and gear shift (automatic transmission, shifting between reverse, drive, and neutral). With the core system only operating, the vehicle can follow a given path of waypoints. If obstacles are detected to lie on that path, the behavior control computes a revised path that goes around the obstacle. The vehicle control module translates the deviation of measured location from the planned path and trajectory into a feedback control signal to the vehicle using proportional integral/differential (PID) control.

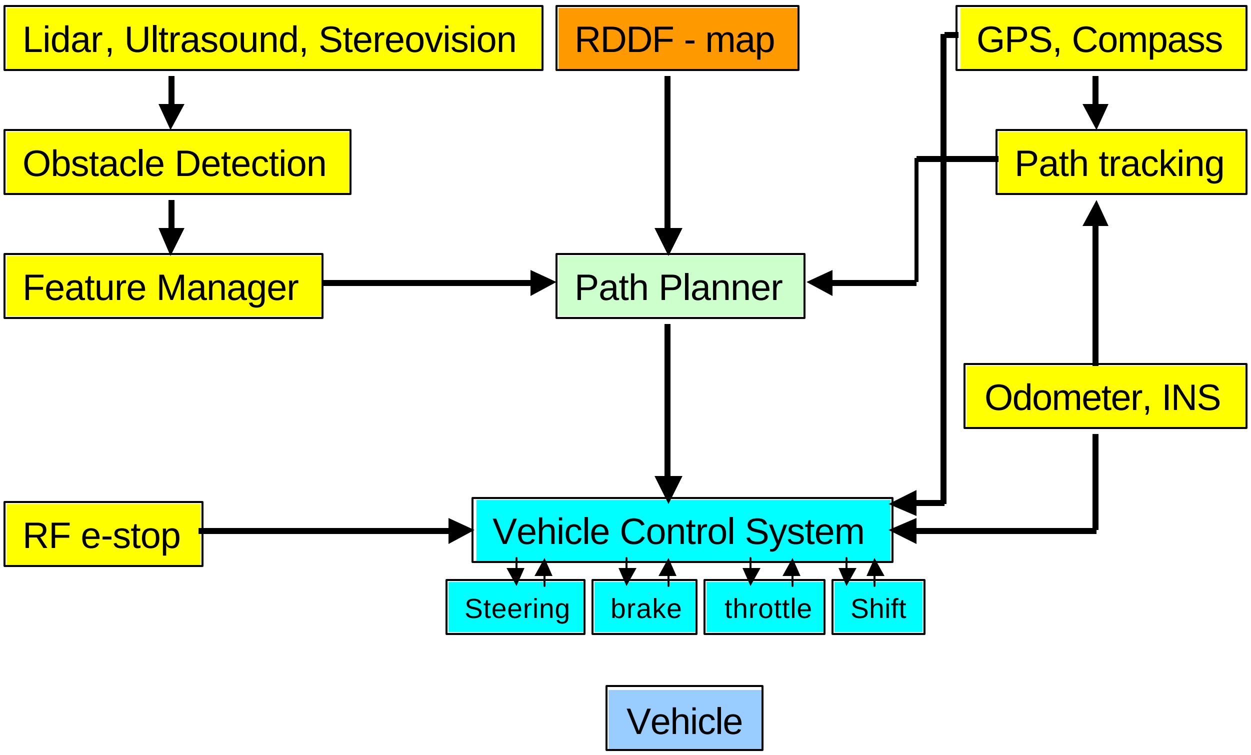

Figure 3. System Architecture.

Processing

We use two 750 MHz Pentium-4 embedded systems built as a PC104+ stack. These two computers do not require active cooling. They perform all the key functions for autonomous driving such as sensor input and processing (from serial ports), path recomputation (for collision avoidance and waypoint following) and vehicle control output. The software is modular. Information is passed between modules using UDP. Data acquisition modules interface to sensors via RS232 or RS422. Sensor processor modules process sensor data to determine vehicle state (current position, heading, and velocity) and to detect obstacles. The path planner module alters the planned path as necessary to avoid obstacles. The vehicle control module takes current vehicle state and the planned path as inputs and adjusts throttle, brake, steering, and gear as necessary to keep the vehicle on course. In addition we have simulation modules that allow for testing of all other modules, with the exception of the data acquisition modules.

Vehicle Power

Source of Power

The locomotion power source is from a 660 cc 4-cycle carbureted internal combustion engine built by Yamaha. The maximum power consumption for the drive train is approximately 35 horsepower or approximately 26 kW. Two portable power generators (Honda Model EU2000i) mounted on the vehicle supply electrical power (4 kW) for computers, sensors, and actuators. A total of 32 gallons of unleaded gasoline supplies the fuel for the vehicle and all the equipment.

Safety Equipment on-board the Challenge Vehicle

Fuel Containment

Fuel is contained in two foam-lined fuel cells protected by a roll cage.

Fire Suppression

A fire extinguisher has been mounted externally on the vehicle in an obvious easily reached open location.

Audio and Visual Warning Devices

A mounted beeping alarm and flashing strobe provide audible and visual warnings as specified by GC rules.

Autonomous Servicing

Refueling

The vehicle will carry sufficient gasoline to complete the entire race

Additional servicing activities

The vehicle will not be autonomously serviced.

Vehicle Performance and Specifications

Top Speed of Vehicle

The top speed of the vehicle is 55 MPH in 4-wheel drive.

Maximum Range of Vehicle

The maximum range of the vehicle under race conditions with full tanks is approximately 300 miles.

Hazardous devices

Other than the vehicle itself and the fuel onboard, there are no hazardous devices. The generators produce 120VAC, protected by common wiring insulation and using conventional outlets.

Tire Properties

The vehicle is based on an ATV style vehicle with large floatation tires. The tires have a chevron style tread pattern that is raised 0.75 inches. On hard surfaces where just the treads are touching, the ground pressure can be as high as 29 pounds per square inch. However, on softer soil where more of the tire surface is touching the ground, the ground pressure is reduced to approximately 5 pounds per square inch. The impact to the environment should be no greater than if a standard 4 wheel drive ATV were driving on the path.

Maximum physical dimensions

The overall vehicle length is 105 inches with a maximum width of 60 inches. The maximum height excluding the DARPA provided E-Stop antenna reaches 65 inches; including the antenna adds an additional 26 inches. The vehicle (excluding the human driver, but with computer systems installed) weighs appoximately1500 pounds.

Localization

The very first step after obtaining the DARPA RDDF file is to improve the given route based on existing map data. Such data exists in the form of published maps and has been acquired by predriving certain roads prior to the course area being placed off limits. For the Grand Challenge Event, during the two hours between obtaining the RDDF file and the actual vehicle start, a reference path is computed which includes the DARPA waypoints, but also creates a more refined path at a higher resolution. This reference path is the basis for the vehicle following the given route.

The primary sensor used in estimating vehicle state is a Navcom Starfire GPS system that provides differential location updates at 5Hz rate. A Rockwell Collins GNP-10 provides inertial updates of acceleration and angular rate at 50 Hz through accelerometers and gyros. A TCM2 magnetometer provides roll, pitch, and yaw data at 16 Hz. A speedometer encoder provides speed data at a variable rate, depending on the speed of the vehicle. A Kalman filter fuses these data streams into an estimate of the actual location, heading, and velocity. Depending on whether GPS data are available at all or if they are obtained in differential or normal mode, a different set of error covariance elements is used for the estimation process. Position, speed, and heading can be derived from the GPS system alone. However, use of the Kalman filter to merge the GPS location data with the other sources of vehicle state data allows the system to be driven during an outage of GPS or differential GPS.

Sensing

The main obstacle sensing is based on SICK LIDAR sensors. Two of these sensors are used to scan horizontally, to detect objects that are in the path to be driven. Two other LIDAR sensors scan vertically, to detect surface continuity and discontinuity (negative obstacles). The maximum look-ahead distance of these sensors is 80 m.

Other sensors include a suite of ultrasound sensors, which are mounted to obtain close-range distance measurement of nearby objects. These are used to allow driving in reverse and to navigate between tight walls. The LIDAR sensors cover this case as well, but the ultrasound sensors act as additional redundant sensors, which are less susceptible to dust or fog.

As a mid-range (10 m < R <20m) obstacle sensing system, a stereo vision system jointly developed by Seibersdorf research and ACV, is used. It detects object up to a distance of 25 m and also provides information about road boundaries. The Stereo Vision Sensor consists of a pair of Basler A601f monochrome cameras with a resolution of 656 (H) x 491 (V) and a quantization of 8 bits/pixel. The cameras are connected by a 400MBit-FireWire network to an Embedded Vision System. That system is based on a Texas Instruments TMS320C6414 DSP running at 1GHz and the operating system is DSP/BIOS II from Texas Instruments. The embedded system is responsible for the synchronous acquisition of both images, for execution of the computer vision algorithms, and the communication with the RASCAL feature manager via an Ethernet interface using UDP sockets. The whole stereovision sensor is protected against dust and sunlight by a special housing.

The main task of the stereovision sensor is the detection of obstacles and lane limitations in front of RASCAL. For obstacle detection, a stereo matching method is used. For lane limitation detection, left and right camera images are divided into different regions-of-interest (ROI's). Each ROI is median-filtered and afterwards, a linear gradient filter is used to extract edges. By applying the Hough transformation, line segments are identified in each ROI and grouped together over the whole image to form left and right lane limitation. Lanes are split into fragments, which are by themselves marked as obstacles. With this approach, the integration of this sensor's output into the RASCAL feature manager is straight forward, since all sensor systems use equivalent obstacle representation.

The output of all the sensing systems is fed into a 2D birds-eye view representation of a global map coordinate system within the feature manager. A coordinate transformation provides a common coordinate system in UTM coordinates. Each detected object (from any sensor) is virtually plotted into this map framework. Using an R-tree, the system is able to decide if the planned path intersects with an obstacle. If an object is deemed to lie on the vehicle path, an alternative path is computed, avoiding a collision with the obstacle.

Vehicle Control

The vehicle control module accepts a series of waypoints as well as vehicle state information as its input. Inasmuch as the path planner has recomputed the course to avoid any sensed obstacles and to ensure lateral offsets are not violated, the control module itself is only concerned with accurate waypoint following. Its goal is to keep the vehicle location on the planned path and its trajectory aligned with the waypoint trajectory. Once a waypoint is passed, the system continues to the next waypoint.

If the vehicle becomes stuck, the controller will increase the control output to overcome the force holding the vehicle back. In the future, strategies will be added for specific maneuvers, in response to specific reasons for vehicle being stuck. The vehicle speed in sharp curves is limited, to limit lateral g-forces dependent on the curve's radius, to an actual speed, which would be less than the RDDF file allowed maximum speed.

When a human driver drives the vehicle, all the usual controls are accessible to the driver. The vehicle actuators are powered off for the manual override mode.

System Tests

In the lab environment, we use the GAZEBO toolkit to perform system and vehicle simulations. For outdoor testing, our team has permission to perform autonomous vehicle testing at a future public park site owned by the Conejo Recreation and Park District, the park district for the City of Thousand Oaks.

Also, a number of public off-road sites in the Mojave Desert have been used to test the stability and endurance of our system. These sites selected were all outside the exclusion zone identified by DARPA for Challenge vehicles.

Summary

The all-volunteer SciAutonics / Auburn Engineering team, using the resources of its member owned company, SciAutonics LLC, including help from corporate investors, has built RASCAL specifically to compete in the DARPA Grand Challenge. A suite of sensors identifies obstacles to avoid, and the locations of such obstacles are recorded in the vehicles feature manager. The vehicle path is then defined by a waypoint sequence that is prepared in real time by the vehicle's science-based path planner that takes as its input the provided RDDF file information along with the output of the feature manager. The vehicle control system then uses a PID closed loop control to follow the waypoint sequence output from the path planner at speeds up to 16 mph.